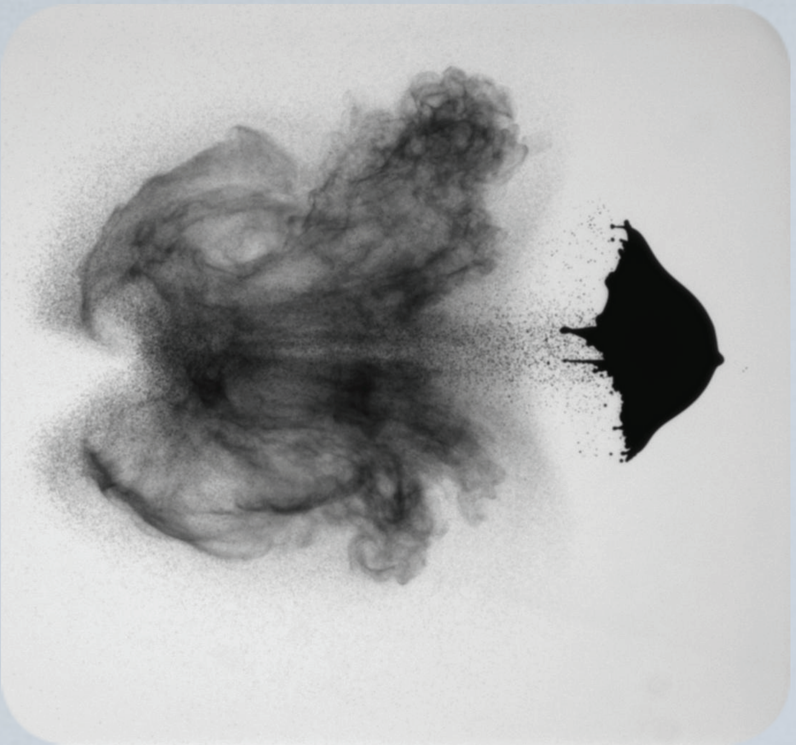
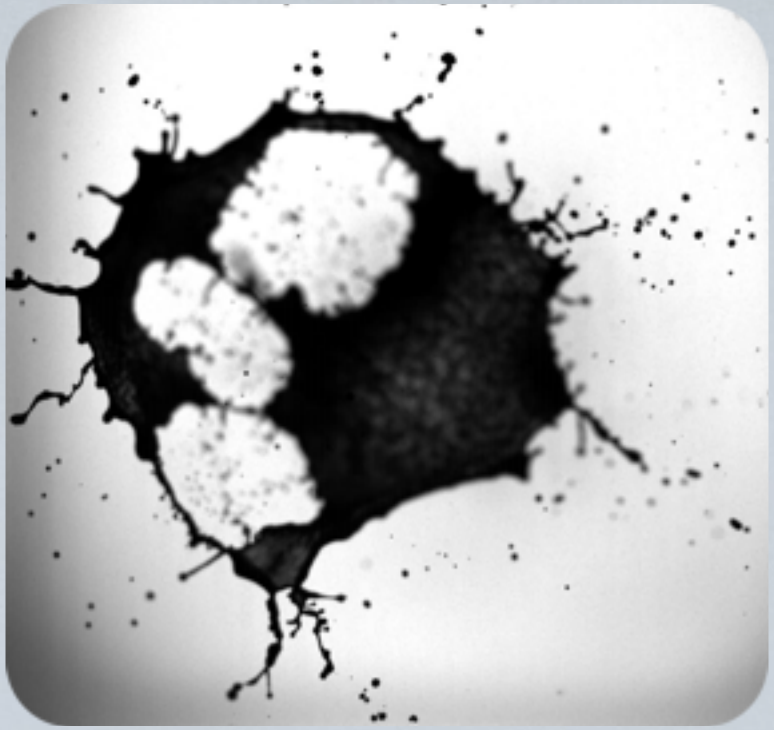
 

Laser impact on a liquid drop

Fluid dynamics of the prepulse

Hanneke Gelderblom, Alexander L. Klein, Dmitry Kurilovich, Oscar Versolato, Emmanuel Villermaux, Henri Lhuissier, Jacco H. Snoeijer and Detlef Lohse

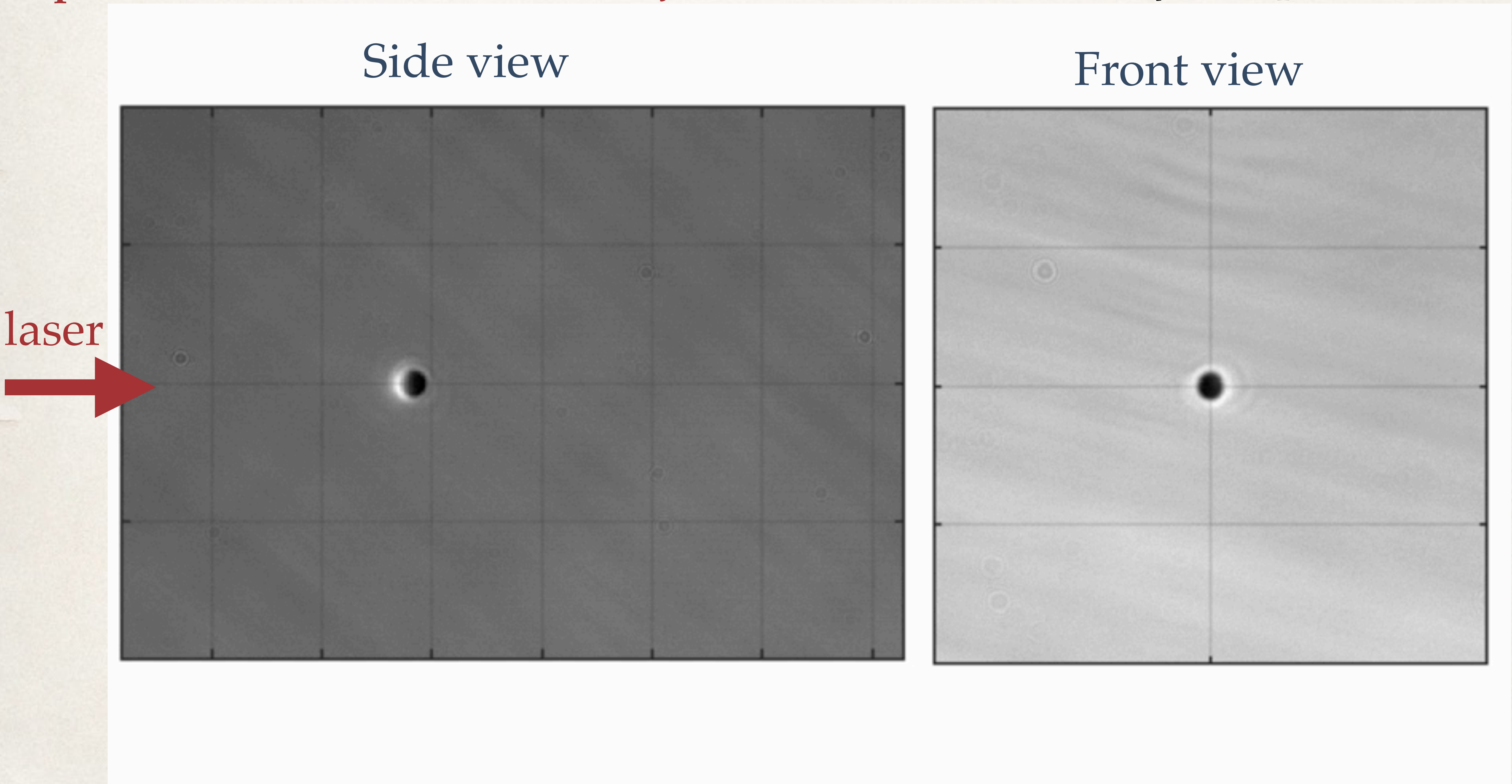
EUV workshop 09-11–2016

PHYSICS OF FLUIDS
UNIVERSITY OF TWENTE.
ASML
FOM

Laser impact on a tin drop

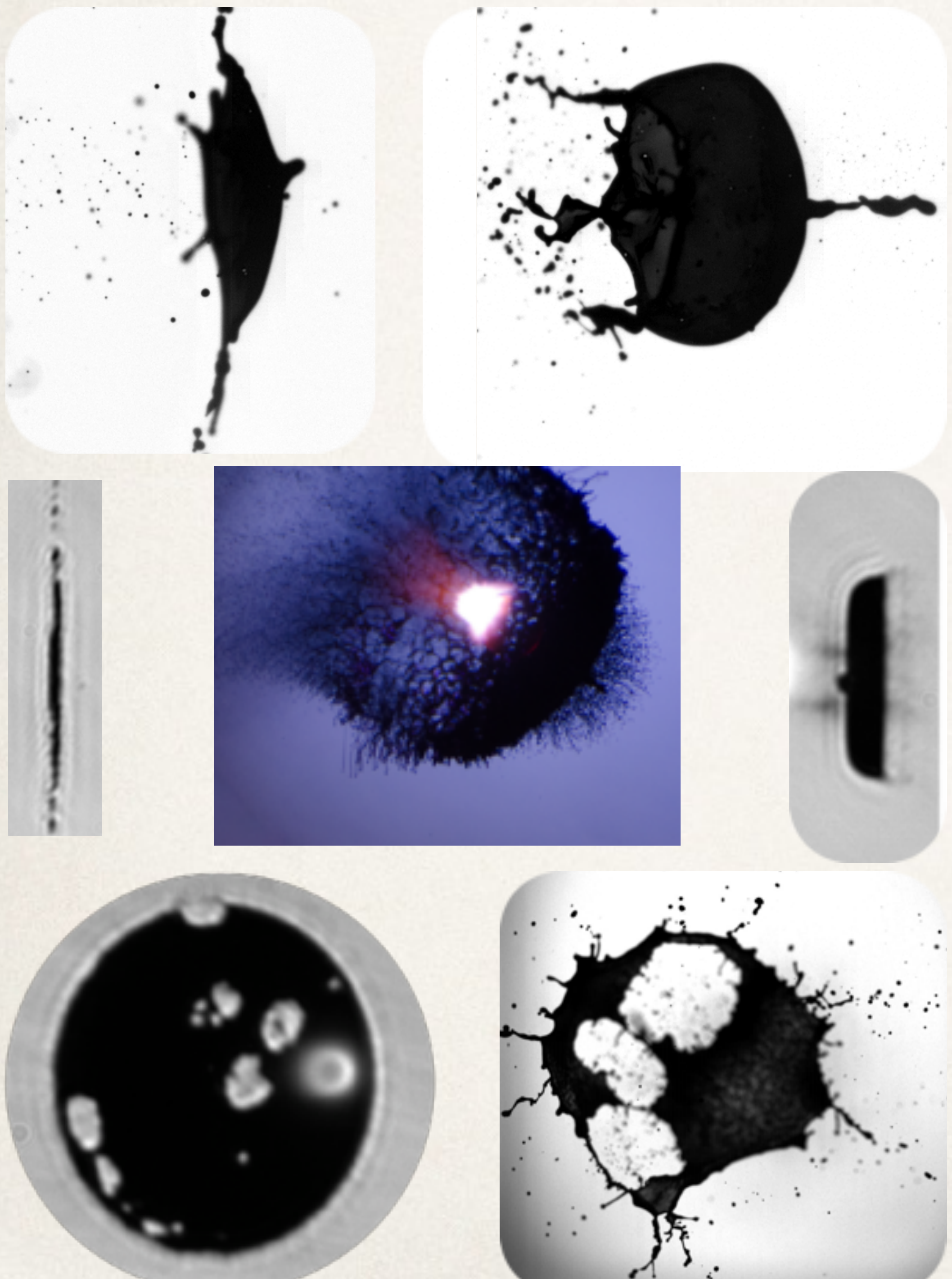
pulsed laser (10 ns, 0.4-160 mJ, 1064 nm)

25-μm liquid tin drop



stroboscopic movie D. Kurilovich & O. Versolato (ARCNL)

The prepulse:
how to shape a drop?



Droplet challenges EUV source:

- Optimal mass distribution for high CE
- Minimum debris

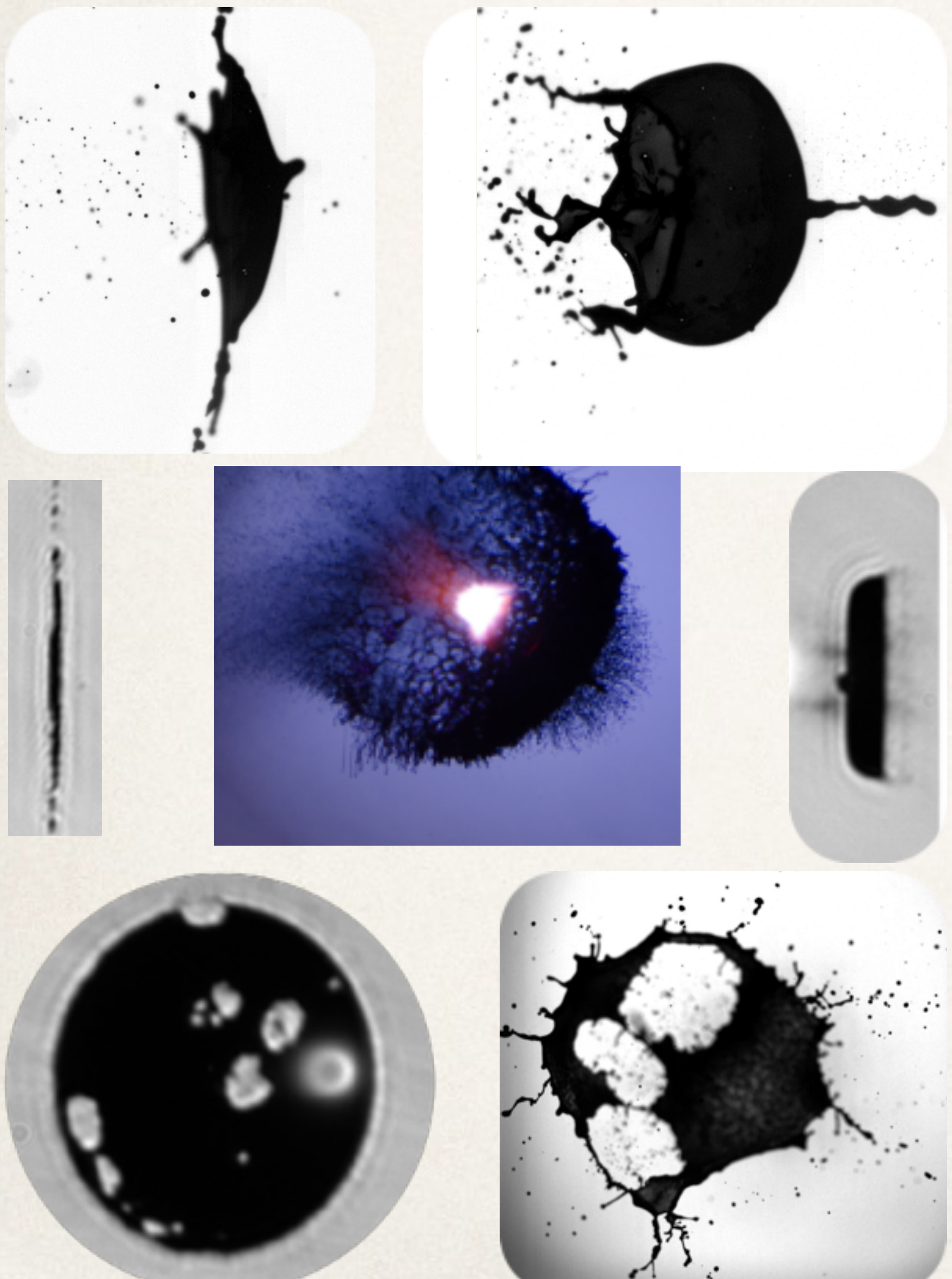
Knobs:

prepulse energy, focus, beam profile, drop size, main pulse timing,…

Required: understanding fluid dynamic response drop to laser impact

➡ How does the drop deform?
➡ How & when does the drop fragment?

The prepulse:
how to shape a drop?



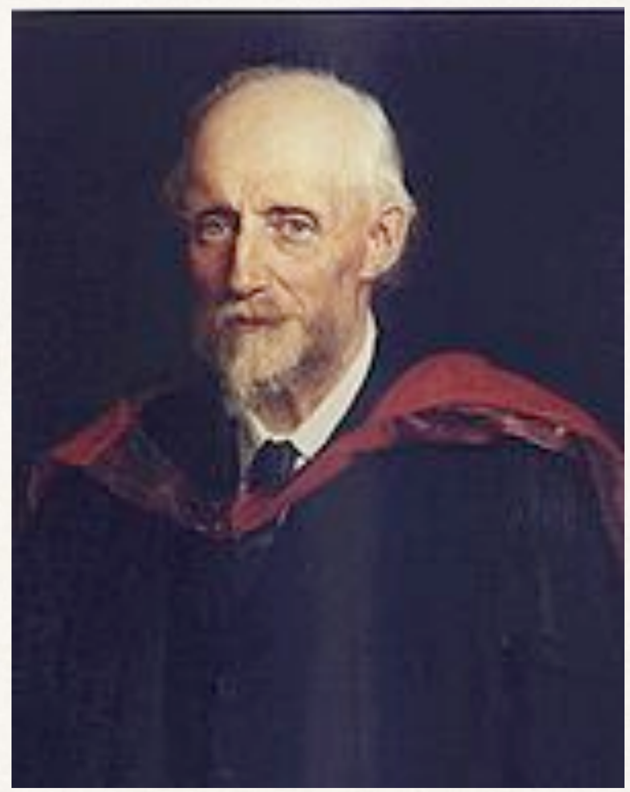
Required: understanding fluid dynamic response drop to laser impact

- ➡ How does the drop deform?
- ➡ How & when does the drop fragment?

Approach: systematic & detailed study with water drops

Why water instead of tin?

Dynamic similarity in fluids

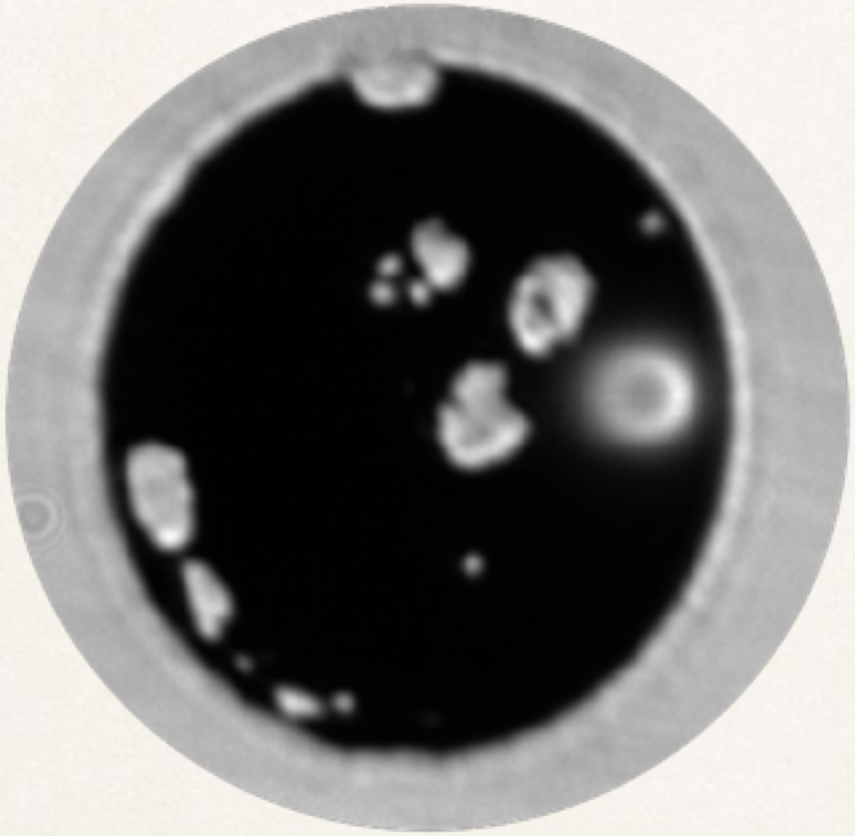


O. Reynolds, 1842-1912

Different length scales, different velocity scales, different fluid properties, but: **similar behaviour**!

Water drops as scale model for tin

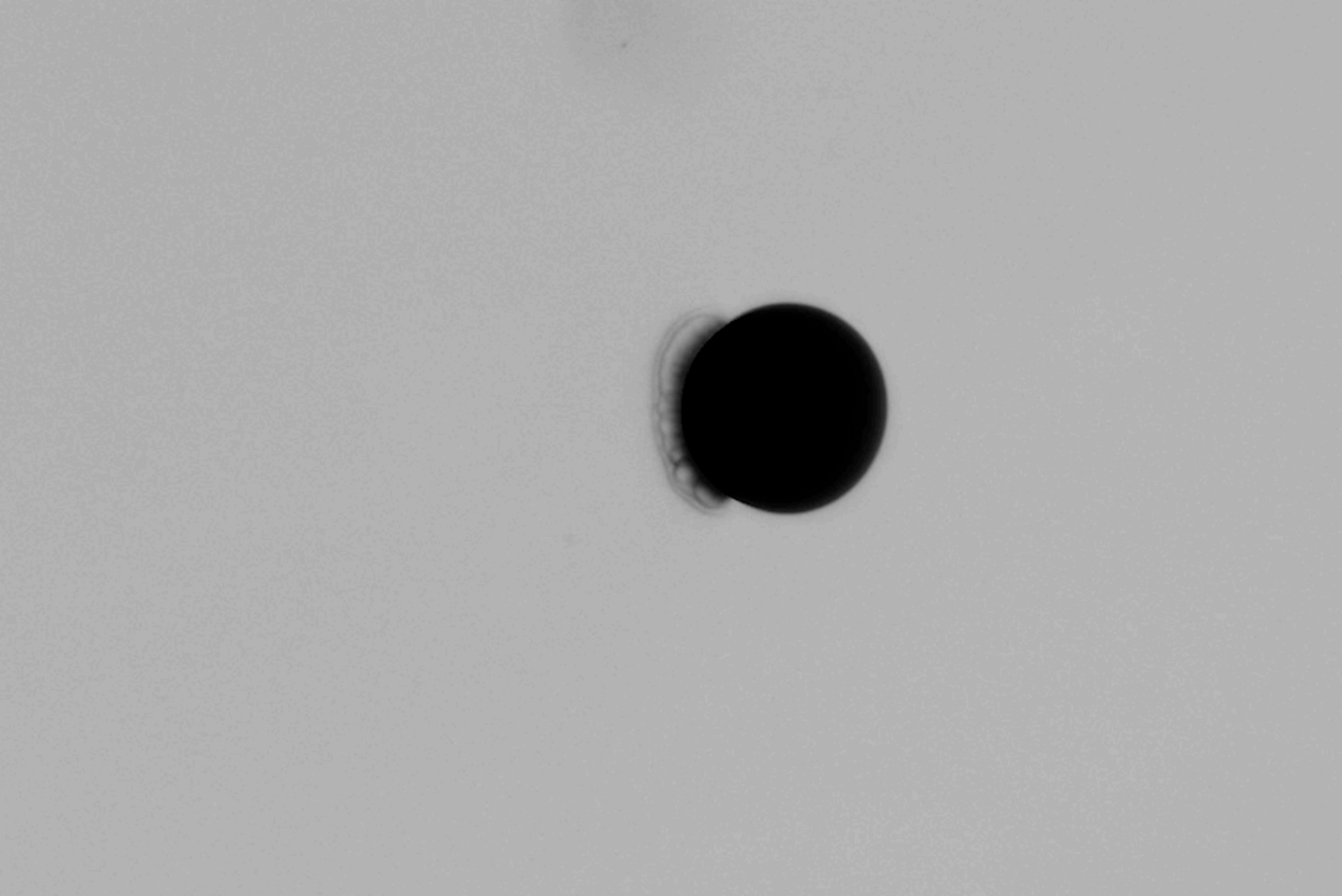
25 μm tin drop, U~100 m/s



1 mm water drop, U~10 m/s

key parameter governing drop deformation & fragmentation

$$\textbf{Weber number} = \frac{\text{kinetic energy}}{\text{surface energy}} = \frac{\rho R_0 U^2}{\gamma}$$

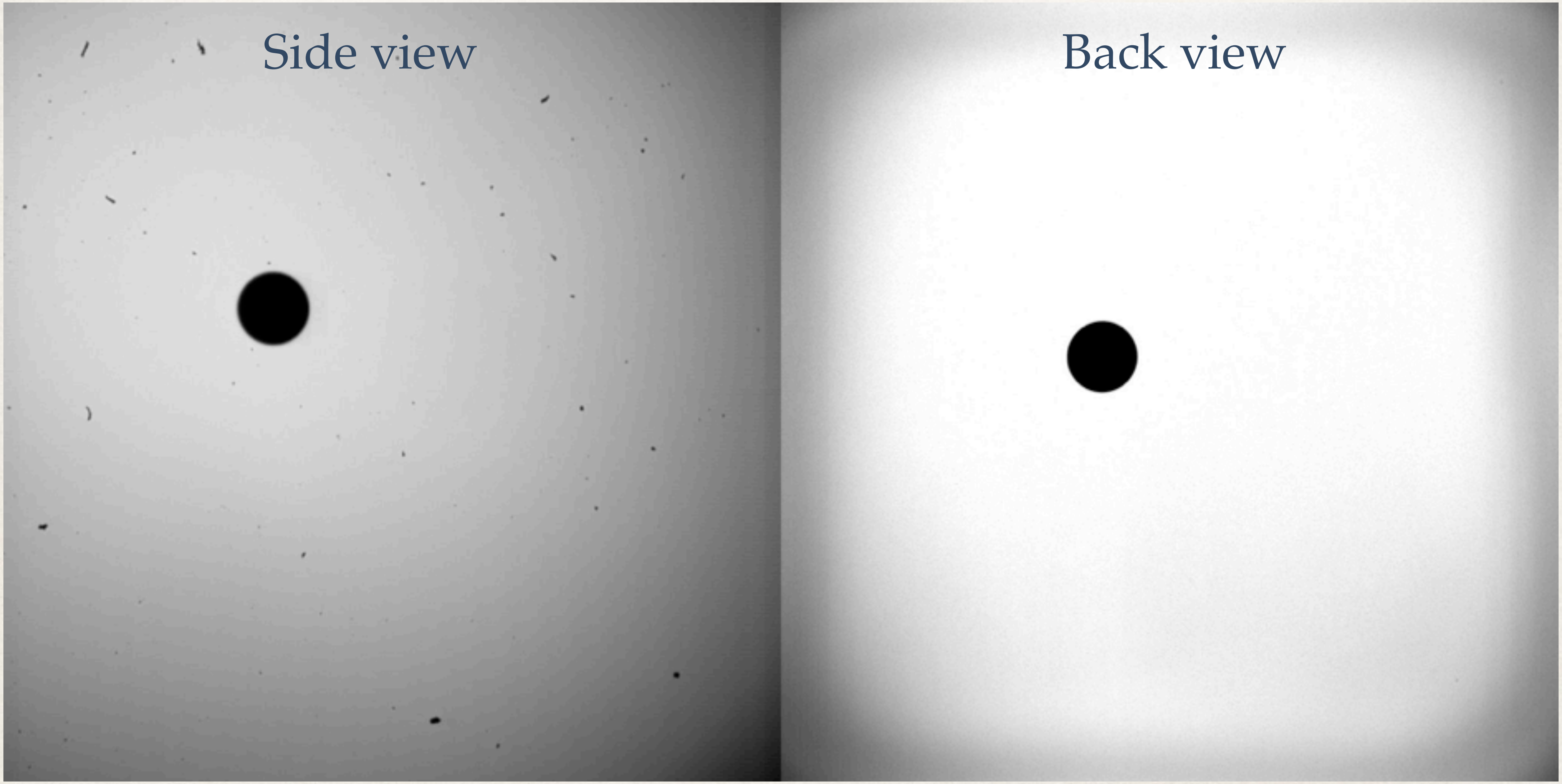


pulsed laser (10 ns, 120-400 mJ, 532 nm)
1-mm dyed water drop

stroboscopic;
effective frame rate 10^7 FPS

Laser impact on a water drop

pulsed laser (10 ns, 120-400 mJ, 532 nm) **1-mm dyed water drop**

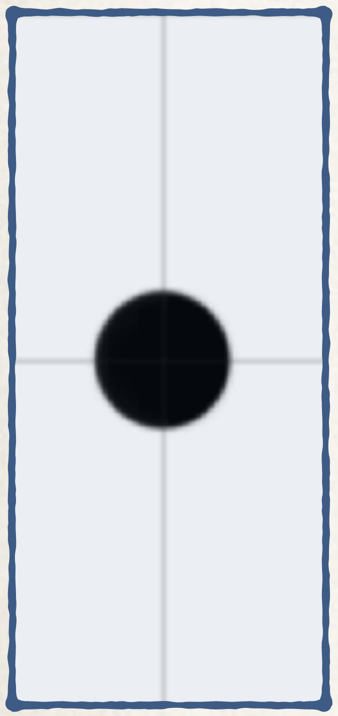


high speed movie: 10 000 FPS

What happens to the drop?

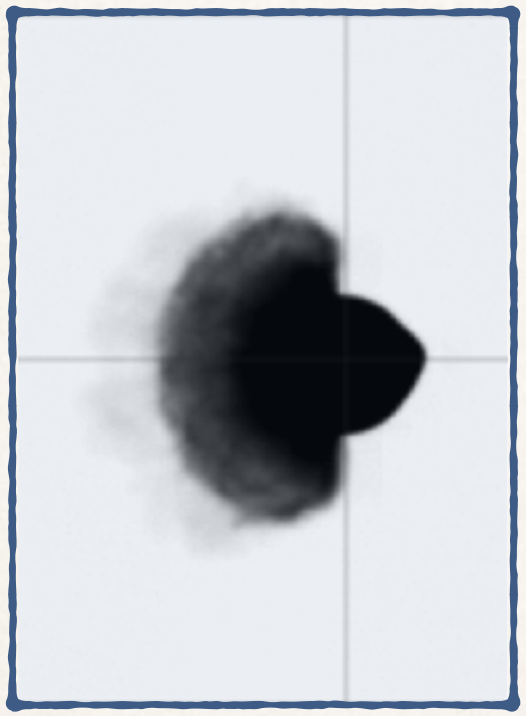
Separation of time scales

$\tau_l \sim 10$ ns



water: $\tau_p \sim$ 1-10 μs

tin: $\tau_p \sim 10$ ns



1. It gets propelled

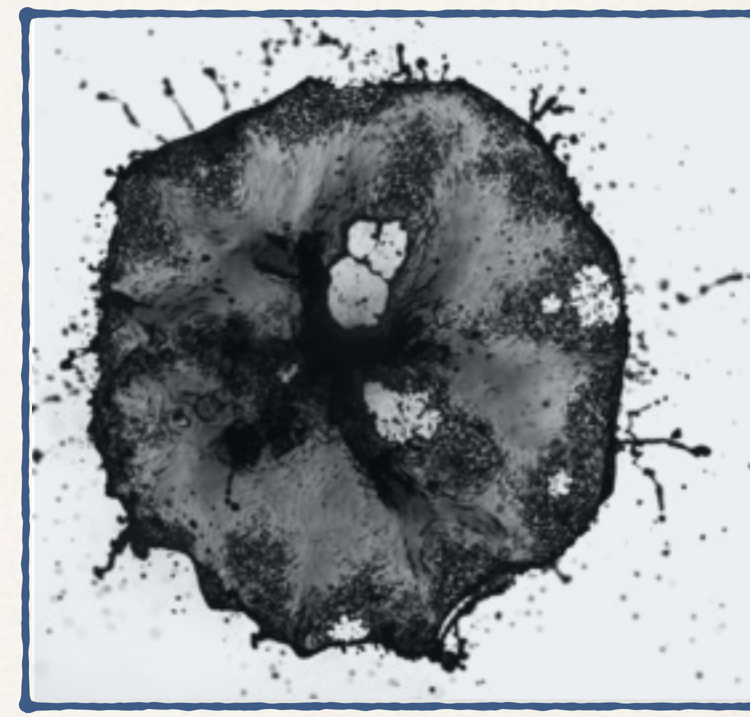
$\tau_i \sim 0.1$ ms

$\tau_i \sim 0.1$ μs

2. It deforms

$\tau_c \sim 1$ ms

$\tau_c \sim 10$ μs



3. It fragments
   a. Rim breakup
   b. Hole nucleation

Klein et al. Phys. Rev. Applied 3 (2015)

What happens to the drop?

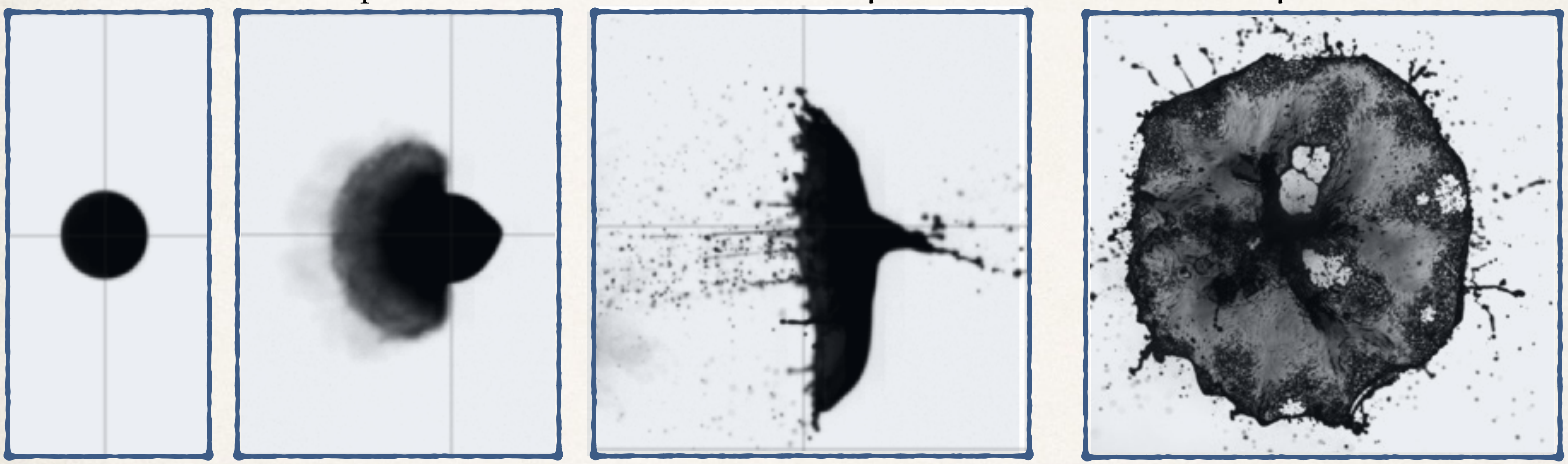
Separation of time scales

$\tau_l \sim 10$ ns

water: $\tau_p \sim$ 1-10 μs
tin: $\tau_p \sim 10$ ns

$\tau_i \sim 0.1$ ms
$\tau_i \sim 0.1$ μs

$\tau_c \sim 1$ ms
$\tau_c \sim 10$ μs



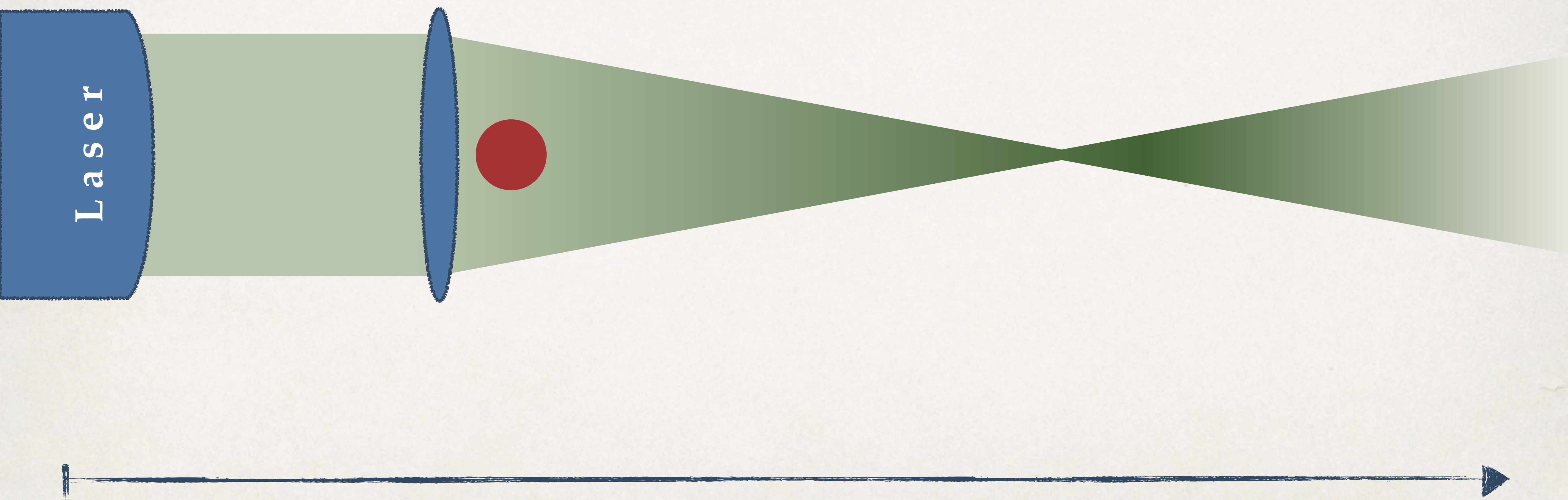
1. It gets propelled

2. It deforms

3. It fragments
a.Rim breakup
b.Hole nucleation

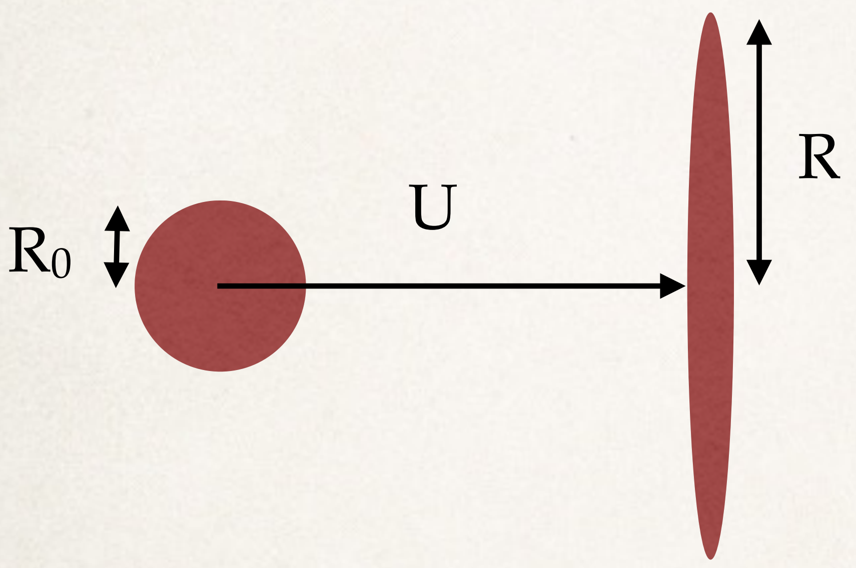
Klein et al. Phys. Rev. Applied 3 (2015)

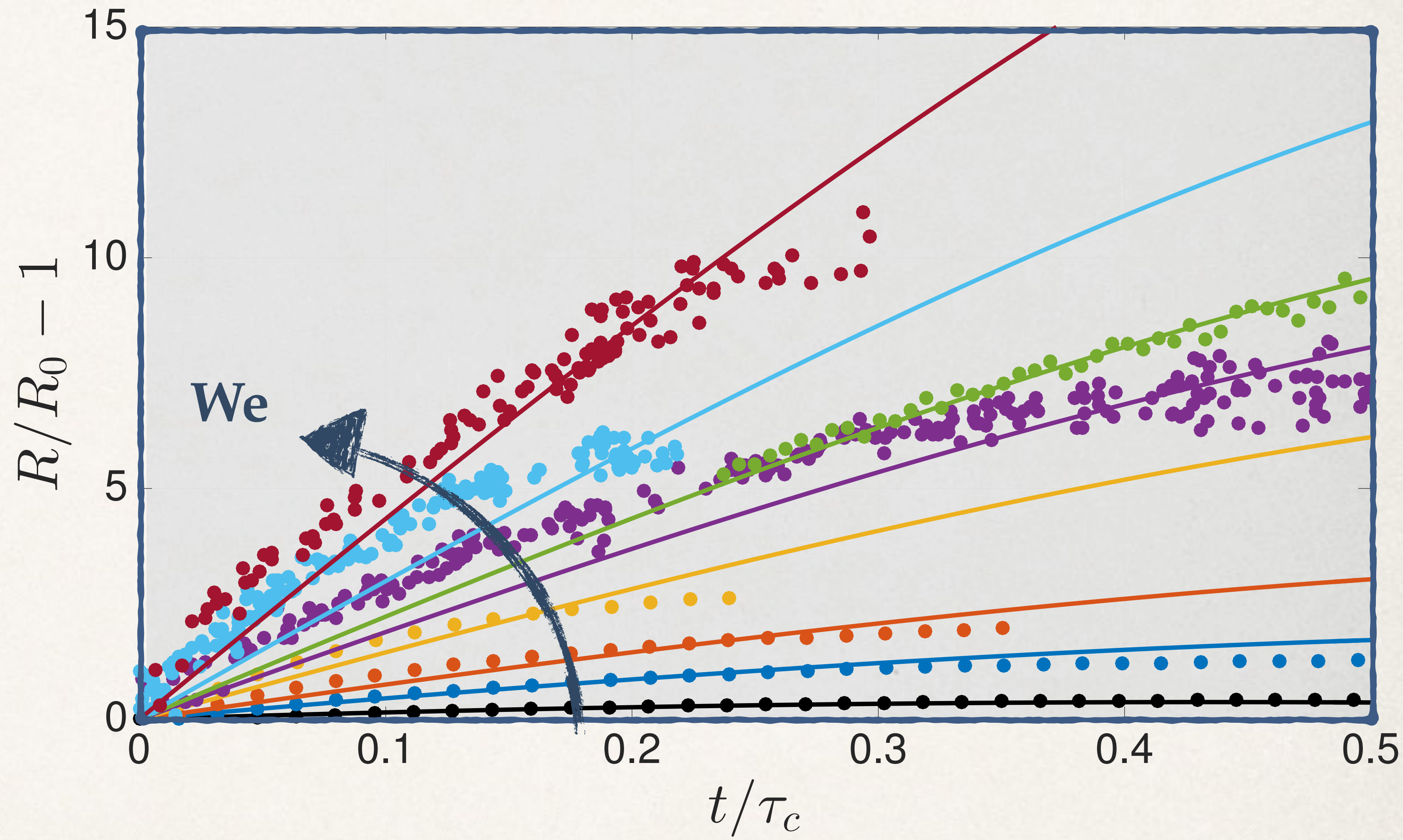
2. The drop deforms



Laser energy, Weber number

Drop expansion:
water & tin collapse onto universal curve





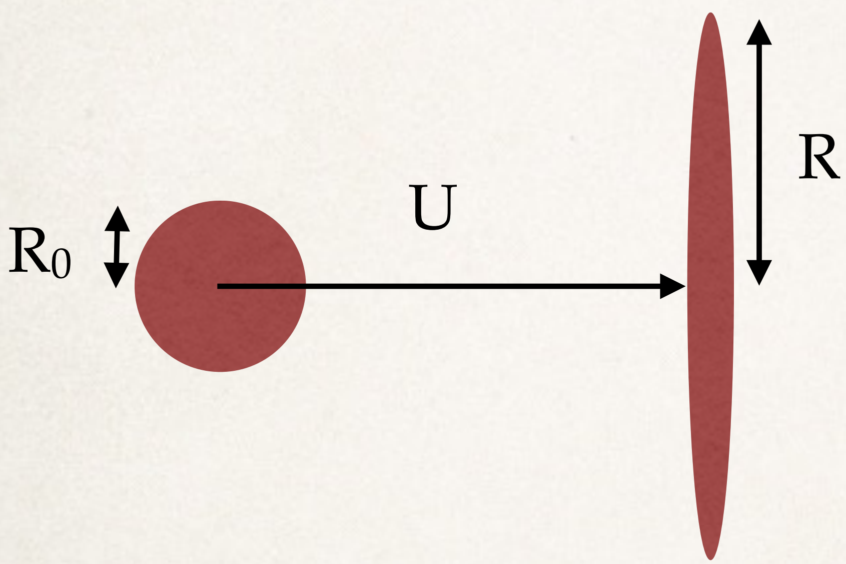
Model for surface-tension limited expansion:

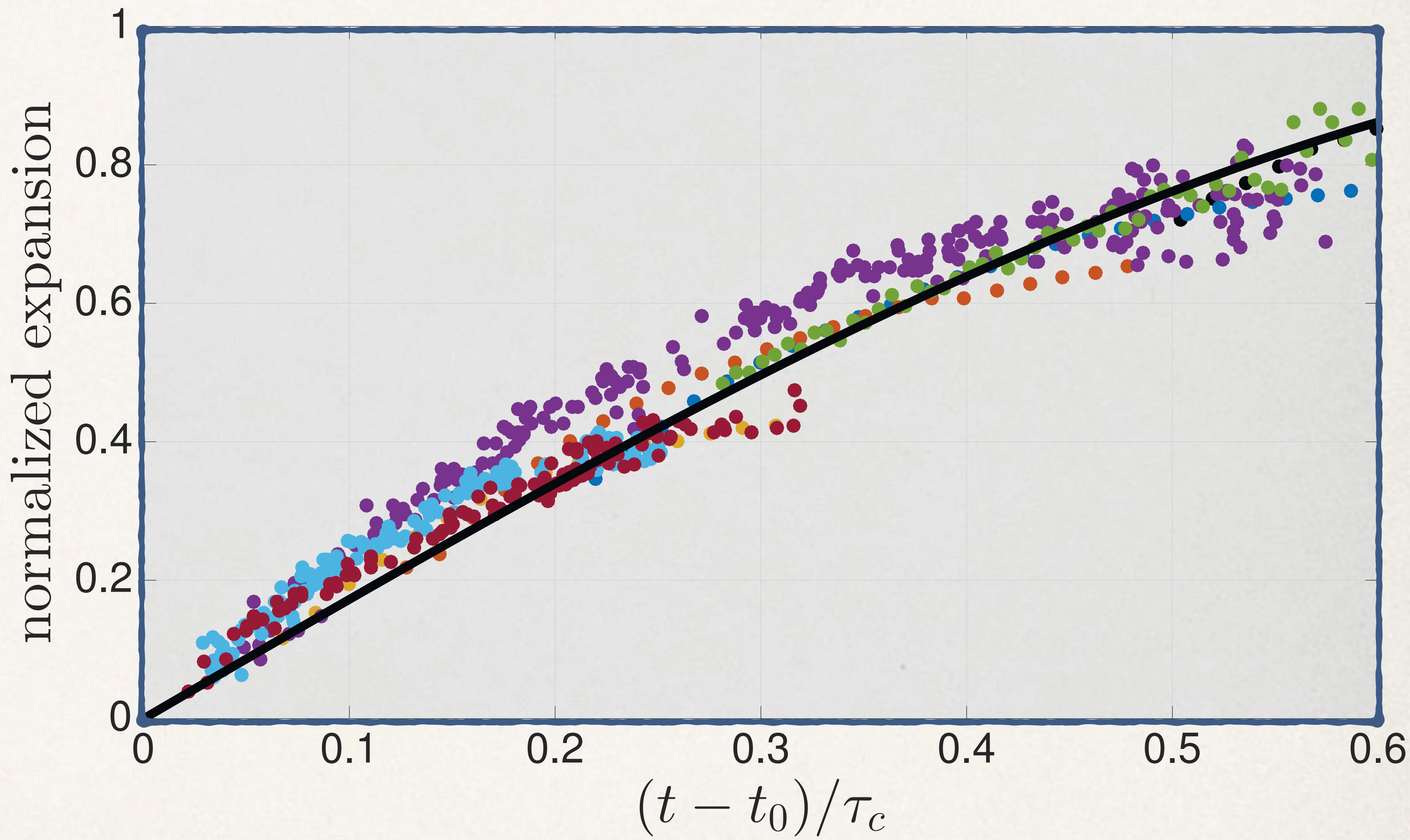
$$\frac{R(t)}{R_0} = \cos(\sqrt{3}t/\tau_c) + \left(\frac{2}{3}\right)^{1/2} \left(\frac{E_{k,d}}{E_{k,cm}}\right)^{1/2} \mathrm{We}^{1/2} \sin(\sqrt{3}t/\tau_c)$$

Gelderblom et al. J. Fluid Mech. 794 (2016)

Drop expansion:

water & tin collapse onto universal curve





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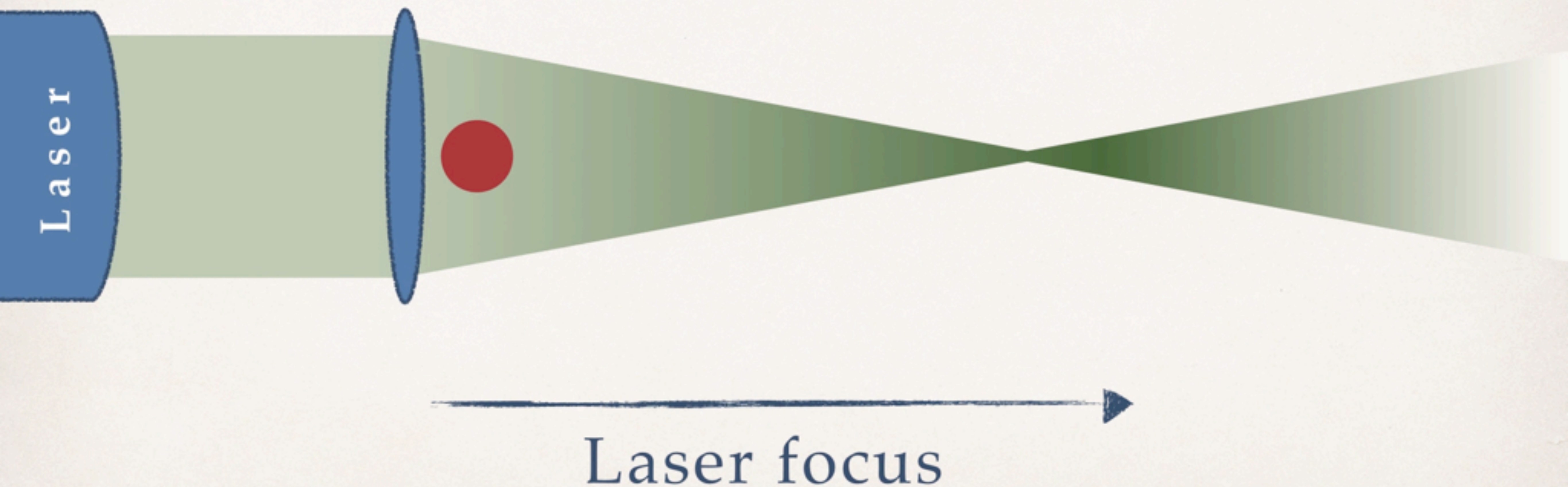
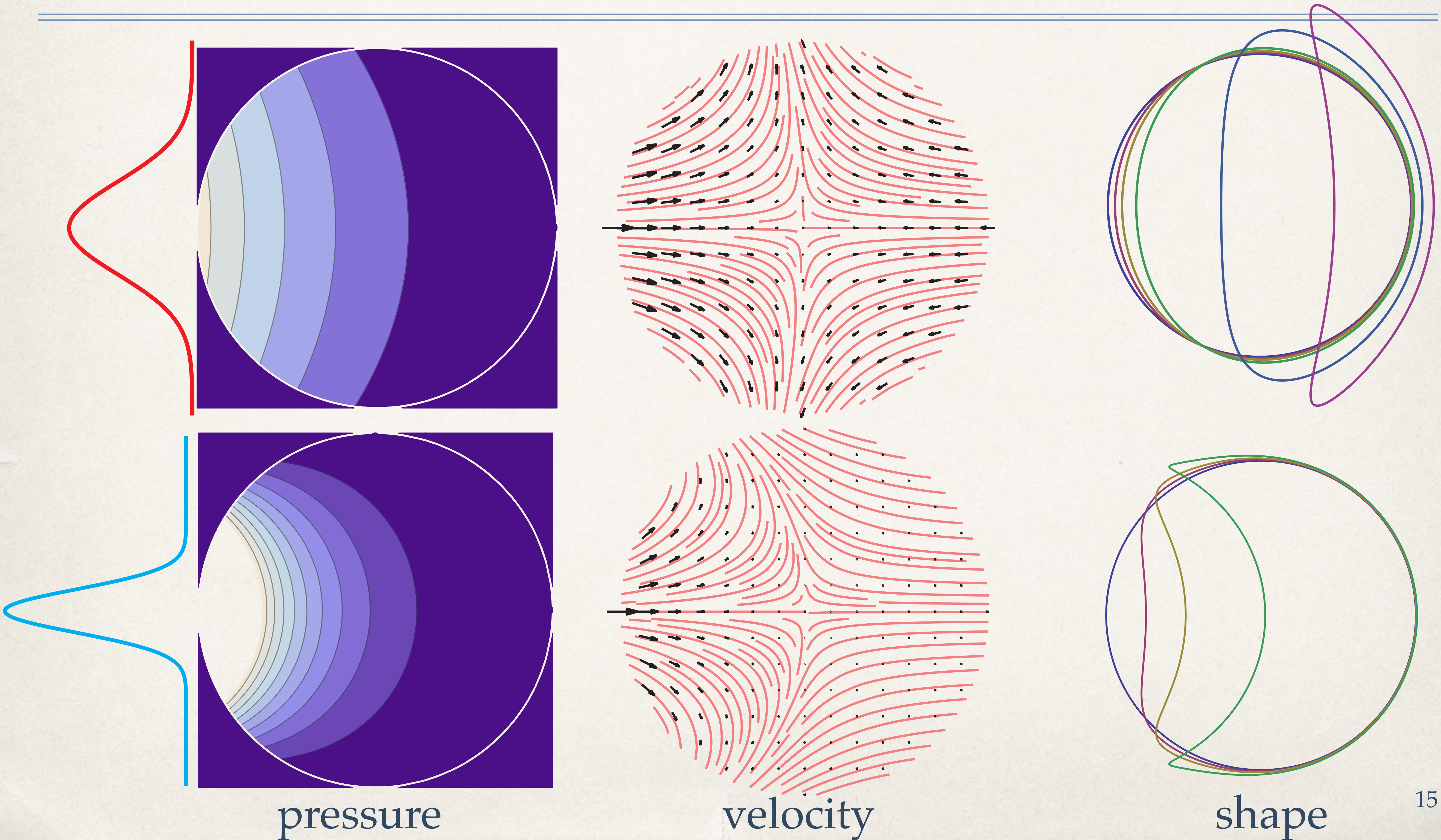
Gelderblom et al. J. Fluid Mech. 794 (2016)
Kurilovich et al. Phys. Rev. Applied 6 (2016)

Tune drop shape by laser focussing

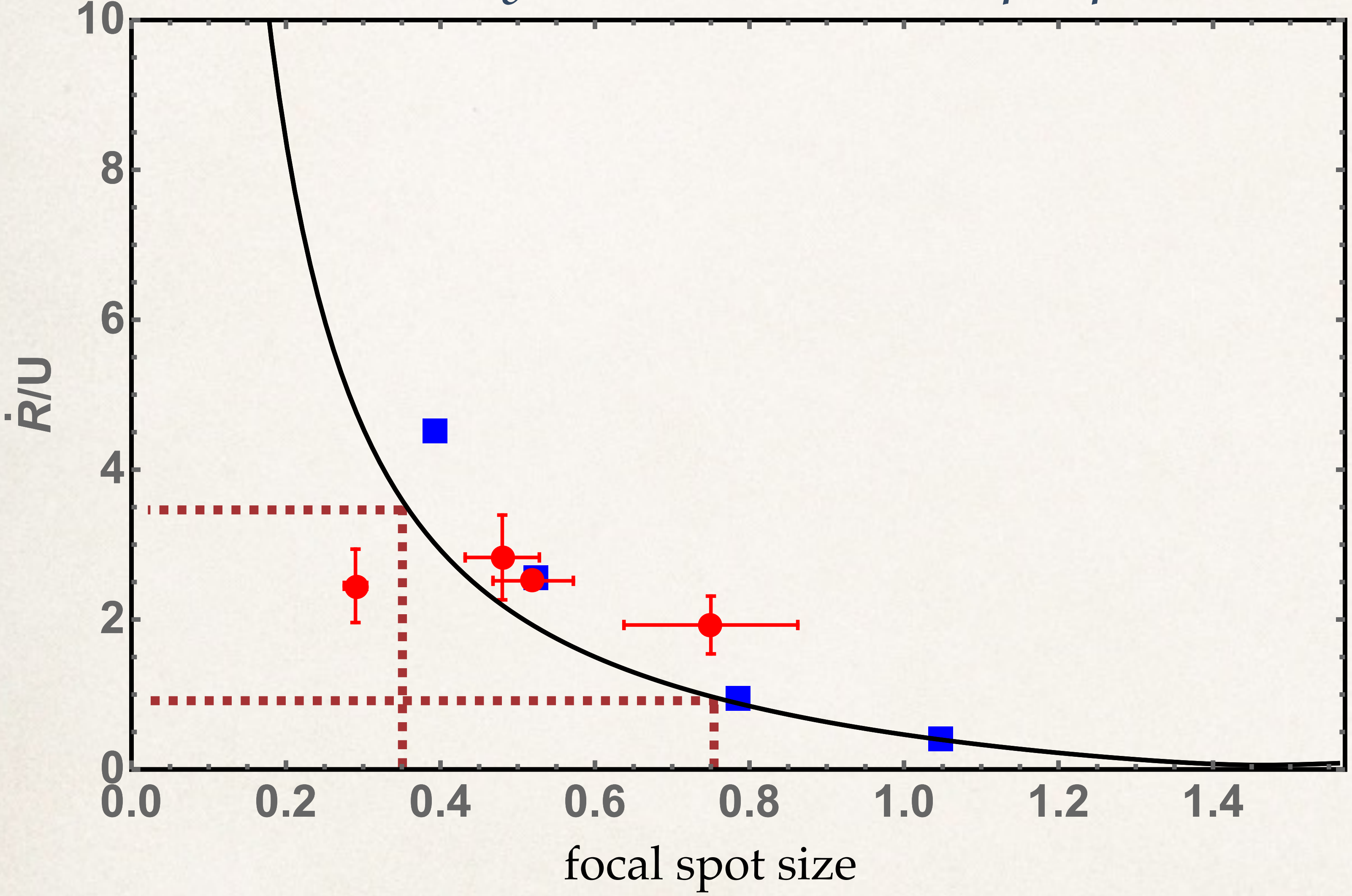


Tune drop shape by laser focussing
analytical model



Faster expansion by decreasing focal spot size

you don't want to propel, but to expand!



Focus ~ drop size
35% of kinetic energy used to deform

Focus ~ 1/2 drop size
85% of kinetic energy used to deform

~3x faster expansion!

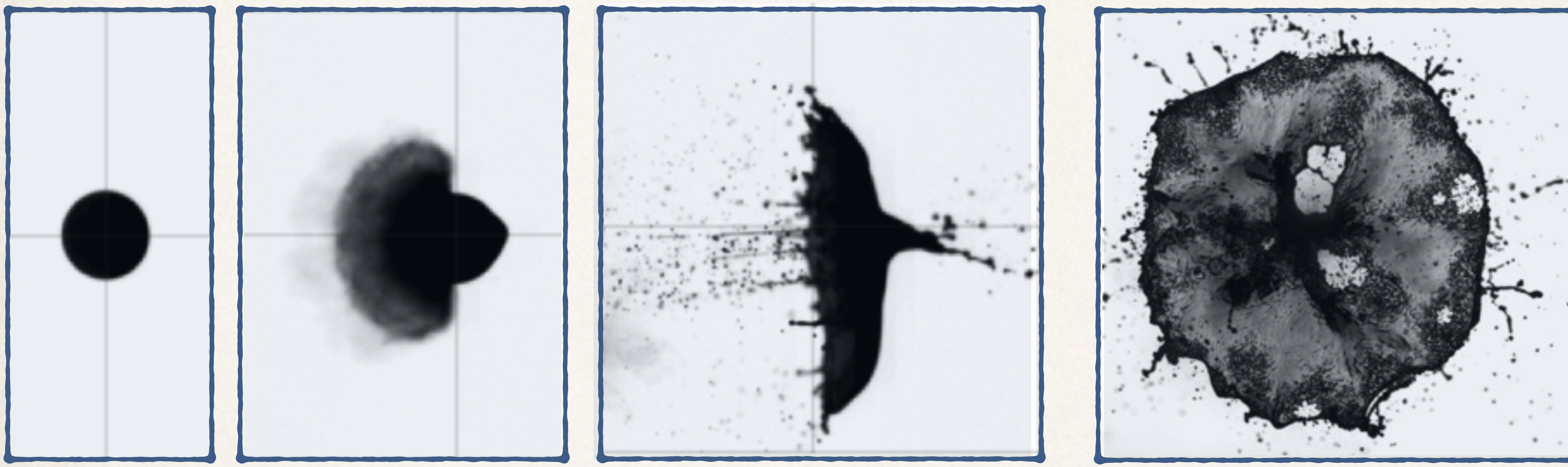
➡ lower PP energy

➡ shoot MP earlier

Gelderblom et al. J. Fluid Mech. 794 (2016)

What happens to the drop?

Separation of time scales

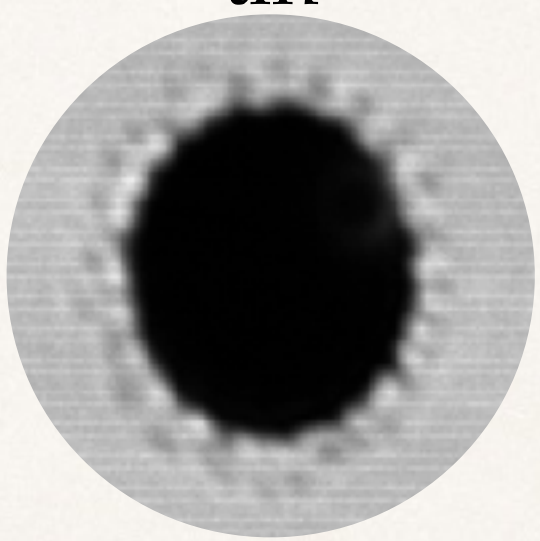


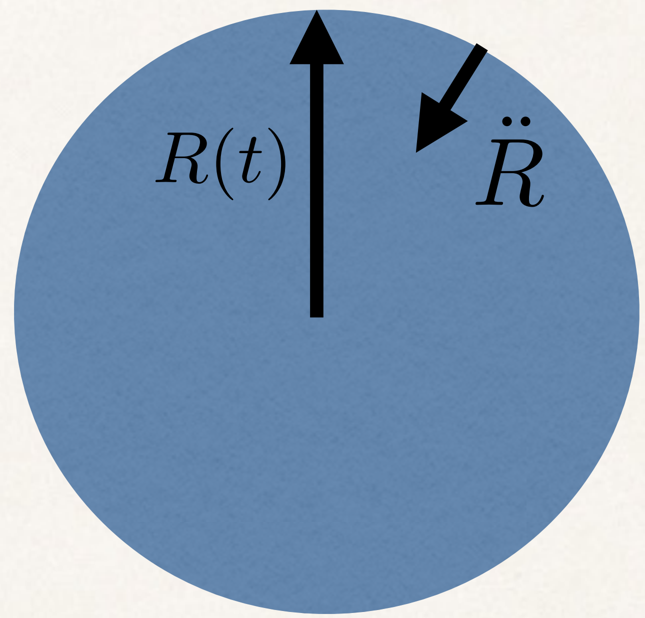
1. It gets propelled
2. It deforms
3. It fragments
    a. Rim breakup
    b. Hole nucleation

3a. Rim breakup
Fluid dynamic instability

water

tin





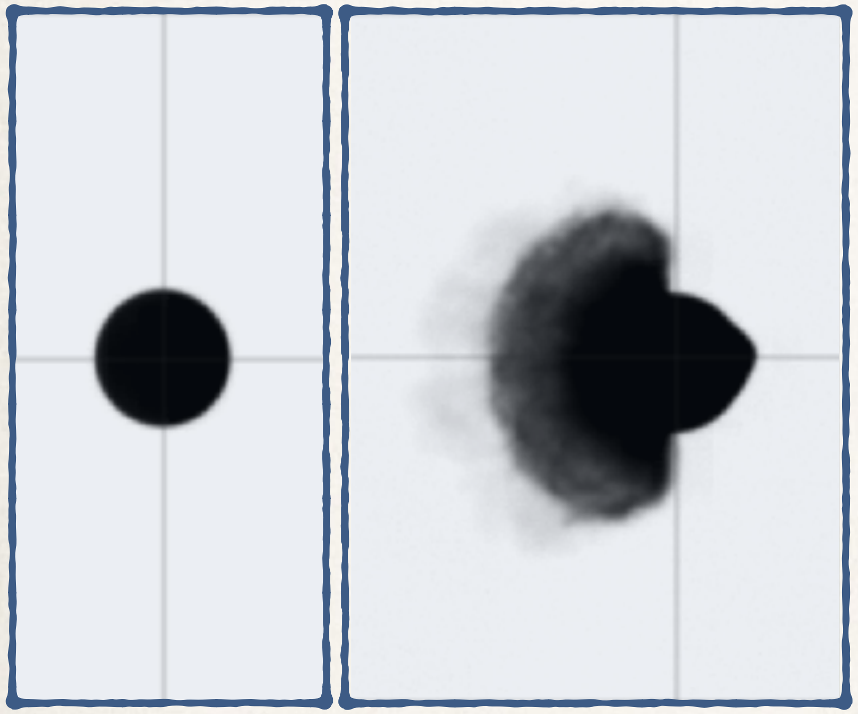
Predictions:

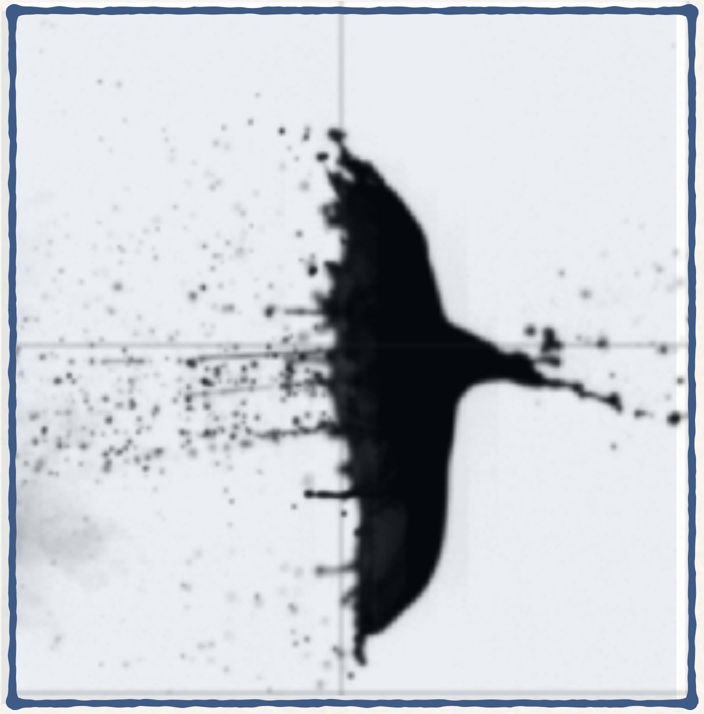
$$\omega \sim \left(\frac{\rho \ddot{R}^3}{\gamma}\right)^{1/4}$$

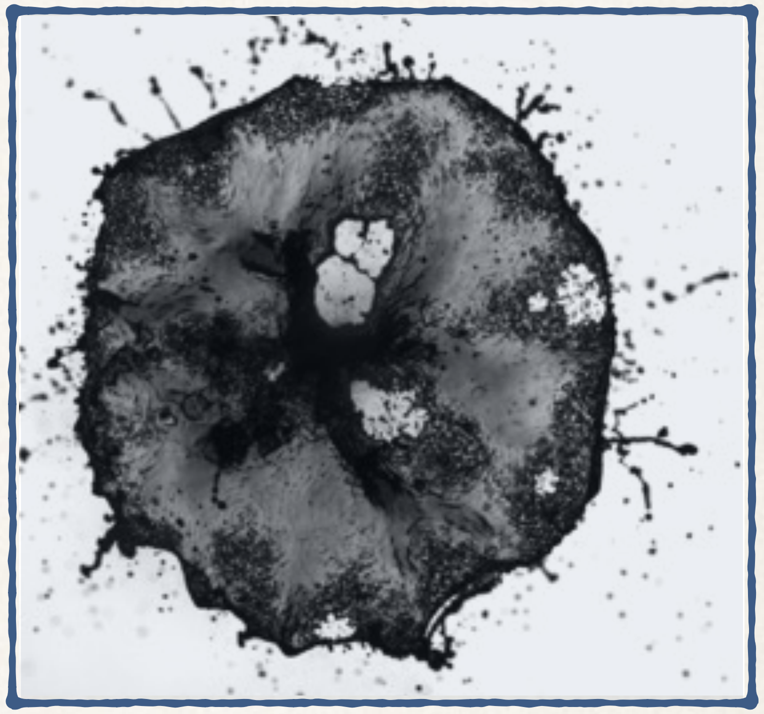
$$\lambda \sim \left(\frac{\gamma}{\rho \ddot{R}}\right)^{1/2}$$

Villermaux & Bossa, Drop fragmentation upon impact, J. Fluid Mech. 668 (2011)

Conclusions







- Key parameter drop deformation & fragmentation: Weber number
- Water & tin scalable
- Focussed laser: faster expansion, curved shape
- Phase diagram for different expansion and fragmentation regimes

Acknowledgements

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Oscar Versolato

Thank you for your attention!